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WIND ENERGY

TECHNICAL MEMORANDUM

LOW SPEED AERODYNAMICS LABORATORY

SUMMARY REPORT

COMPUTER PROGRAM FOR AERODYNAMIC ANALYSIS OF VERTICAL AXIS WIND TURBINE

THIS WORK WAS PERFORMED FOR NRC UNDER CONTRACT

BY

GasTOPS Ltd.
OTTAWA

NOVEMBER 1982

Canada

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GTL-TR-19-10.5
Summary Report: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine

Prepared for:

National Research Council
Ottawa, Ontario
(Contract #13SR.31155-2-4601)

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List of Symbols

c	blade chord
c_o	blade chord at equator, y = 0
C_D	section drag coefficient
C_{DMIN}	minimum value of C_D
C_N, C_T	coefficients of local blade forces per unit span ΔF_N and ΔF_T respectively; $C_N = (\Delta F_N/0.5\rho W^2 c)$ etc.
C_L	section lift coefficient
C_P	power coefficient, $(P/0.5\ \rho V_E^3 A)$
C_Q	time-average overall torque coefficient $(Q/0.5\ \rho V_E^2 AR)$
$\overline{DW}$	time-average downwind force per unit streamtube area exerted by the fluid on an actuator disc element
ΔF_{DW}, ΔF_{CW}, ΔF_T, ΔF_N	local blade forces per unit span (downwind, crosswind, tangential, normal)
H	height of the VAWT rotor
K_P	power coefficient, $(P/0.5\ \rho(\omega R)^3 A)$
K_Q	time-average overall torque coefficient, $(Q/0.5\ \rho(\omega R)^2 AR)$
n_y, n_ψ	number of vertical and azimuthal increments, respectively, into which the swept surface is sub-divided
N	number of blades

ΔQ	local blade torque per unit span
r	radius from axis to blade at any y; see Figure 1
R	equatorial radius of rotor
Re	Reynolds number, (Wc/ν)
U	blade speed, ωR
V_O	ambient wind speed at any height
V_{OREF}	ambient wind speed at the reference height $Z = Z_{REF}$
V_1	equilibrium wind speed in any streamtube between disc 1 and disc 2
V_2	equilibrium wind speed in any streamtube downstream of disc 2
V_D	wind speed in any streamtube in the plane of the actuator disc
V_E	ambient wind speed at height Z_E
W	resultant velocity relative to a blade section in the airfoil plane at any instant
y	height above equatorial plane
Z	height above ground level
Z_E	height of equatorial plane above ground level
Z_{REF}	reference height for defining ambient wind speed
Z_O	a terrain-roughness parameter
α	instantaneous angle of attack
α_m	a modified angle of attack
α_O	angle of attack for zero lift

$\dot{\alpha}$	time derivative of α
β	angle of the relative velocity vector
γ, γ_o	toe-in angle of blade section at any y and at y = 0 respectively
δ	angle of swept surface to the vertical; see Figure 1
$\Delta y, \Delta\psi$	increments of y and ψ in discretization scheme
ν	kinematic viscosity of the fluid
ρ	density of the fluid
ψ	azimuthal position co-ordinate; see Figure 1
ω	rotational speed of the VAWT in radians per unit time

ABSTRACT

A computer program for the aerodynamic analysis of vertical axis wind turbines (VAWT) has been developed by the National Research Council of Canada. The program has been designed to provide maximum flexibility and ease of use. It is operated interactively and little familiarity with computers is required of the user for successful running.

This document is intended to provide an overview of the program and its capabilities. It is presented in terms of a description of the various configurations of VAWT that can be analyzed, a brief review of the aerodynamic theory used in the analysis and a description of the computer programs in terms of structure and usage. Detailed information on any of these aspects is available in supporting project documentation:

"Analysis Report: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", GasTOPS Limited report number GTL-TR-19-10.1, prepared for NRC under Contract No. 13SR.31155-2-4601, June 1982.

"Program Document: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", GasTOPS Limited report number GTL-TR-19-10.2, prepared for NRC under Contract No. 13SR.31155-2-4601, October 1982.

"Test Report: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", GasTOPS Limited report number GTL-TR-19-10.3, prepared for NRC under Contract No. 13SR.31155-2-4601, November 1982.

"User's Manual: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", GasTOPS Limited report number GTL-TR-19-10.4, prepared for NRC under Contract No. 13SR.31155-2-4601, November 1982.

The development work was performed by GasTOPS Ltd. of Ottawa under contract to the NRC.

RÉSUMÉ

Le Conseil national de recherches du Canada a mis au point un programme ordinateur d'analyse aérodynamique des éoliennes à axe vertical (VAWT). Ce programme est d'une souplesse maximale et d'utilisation facile. Comme il est interactif, l'utilisateur n'a pas à bien connaître l'informatique pour s'en servir avec succès.

Le présent document donne un aperçu du programme et de ses possibilités. On y précise les différents types d'éoliennes pouvant être analysées. On y présente rapidement la théorie aérodynamique sur laquelle repose l'analyse et on y décrit le programme ordinateur des points de vue de sa structure et de son utilisation. Des renseignements détaillés sur chacun de ces points sont donnés dans les documents ci-après:

"Analysis Report: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", rapport GTL-TR-19-10.1 de GasTOPS Limited, contrat CNR n° 13SR.31155-2-4601, juin 1982.

"Program Document: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", rapport GTL-TR-19-10.2 de GasTOPS Limited, contrat CNR n° 13SR.31155-2-4601, octobre 1982.

"Test Report: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", rapport GTL-TR-19-10.3 de GasTOPS Limited, contrat CNR n° 13SR.31155-2-4601, novembre 1982.

"User's Manual: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", rapport GTL-TR-19-10.4 de GasTOPS Limited, contrat CNR n° 13SR.31155-2-4601, novembre 1982.

Les travaux de développement ont été exécutés par la société GasTOPS Limited d'Ottawa, sous contrat passé avec le CNR.

1. Introduction

A computer program for the aerodynamic analysis of vertical axis wind turbines (VAWT) has been developed by the National Research Council of Canada. The program has been designed to provide maximum flexibility and ease of use. It is operated interactively and little familiarity with computers is required of the user for successful running.

This document is intended to provide an overview of the program and its capabilities. It is presented in terms of a description of the various configurations of VAWT that can be analyzed, a brief review of the aerodynamic theory used in the analysis and a description of the computer programs in terms of structure and usage. Detailed information on any of these aspects is available in supporting project documentation, references 1, 2, 3, and 4. Summaries of each of these reports are included in the following pages.

The development work was performed by GasTOPS Ltd. of Ottawa under contract to the NRC.

REFERENCE 1: Analysis Report: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine

This report outlines the analysis methods used in a computer program developed for the aerodynamic analysis of vertical axis wind turbines. All the main analysis methods and equations are presented, but details of the actual computer program are documented elsewhere.

The main theoretical model used in the program is the double multiple streamtube method, a momentum/blade-element method. This is supplemented by a dynamic stall model.

The program can analyze vertical axis wind turbines of virtually any geometry. Wind speed can vary with height according to either a power law or a log law. The program can provide predictions of instantaneous load distributions and blade loads as well as overall loads and performance.

REFERENCE 2: Program Document: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine

This document describes the design and structure of the software developed to perform aerodynamic analysis of vertical axis wind turbines.

The program structure is explained by means of hierarchy diagrams, block diagrams and flowcharts where applicable. Data bases are defined including a list of all variables used in the program. The program is specified with no reference to any particular programming language.

REFERENCE 3: Test Report: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine

This report describes the test procedure and test results for a program written to perform aerodynamic analysis of vertical axis wind turbines. Tests were performed to verify most aspects of the program.

Comparisons of program results were made with results of another program using the same theory, results of other theories and experimental data. Tests were also done to check the human interface aspects of the program.

The program proved to be satisfactory for casual and regular analysis of wind turbines.

REFERENCE 4: User's Manual: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine

This document describes the usage of a computer program written to perform aerodynamic analysis of vertical axis wind turbines. The program was written using standard FORTRAN IV (1966) and is intended for use on most mini-computers.

Instructions are given for all of the options included in the program. An explanation of how to add airfoil data is also included. A listing of the source code is contained in an appendix.

2. General System Description

Figure 1 shows the general configuration of a vertical axis wind turbine. Although the VAWT in figure 1 shows two blades, units with any number of blades can be described. Similarly, the figure shows a Φ type configuration; however, there is no restriction on the general layout insofar as the analysis is concerned. It must, of course, be a vertical axis unit.

Blade layouts are described defining blade radius with respect to distance along the central shaft. This can be either a parabolic functional relationship or a table of values. Since VAWT's are usually built with variable chord blades and setup with a varying toe-in angle, these parameters can be described by tables of values or by a simple constant.

Airfoil section data are required in order to complete the analysis. These data consist of lift and drag data as functions of angle of attack and Reynolds number (R_e). Data are available for the more common airfoil sections; NACA 0012, NACA 0015 and NACA 0018. Provided the lift and drag data are available, there is no restriction on the choice of section used.

The analysis assumes that the wind turbine will be operating

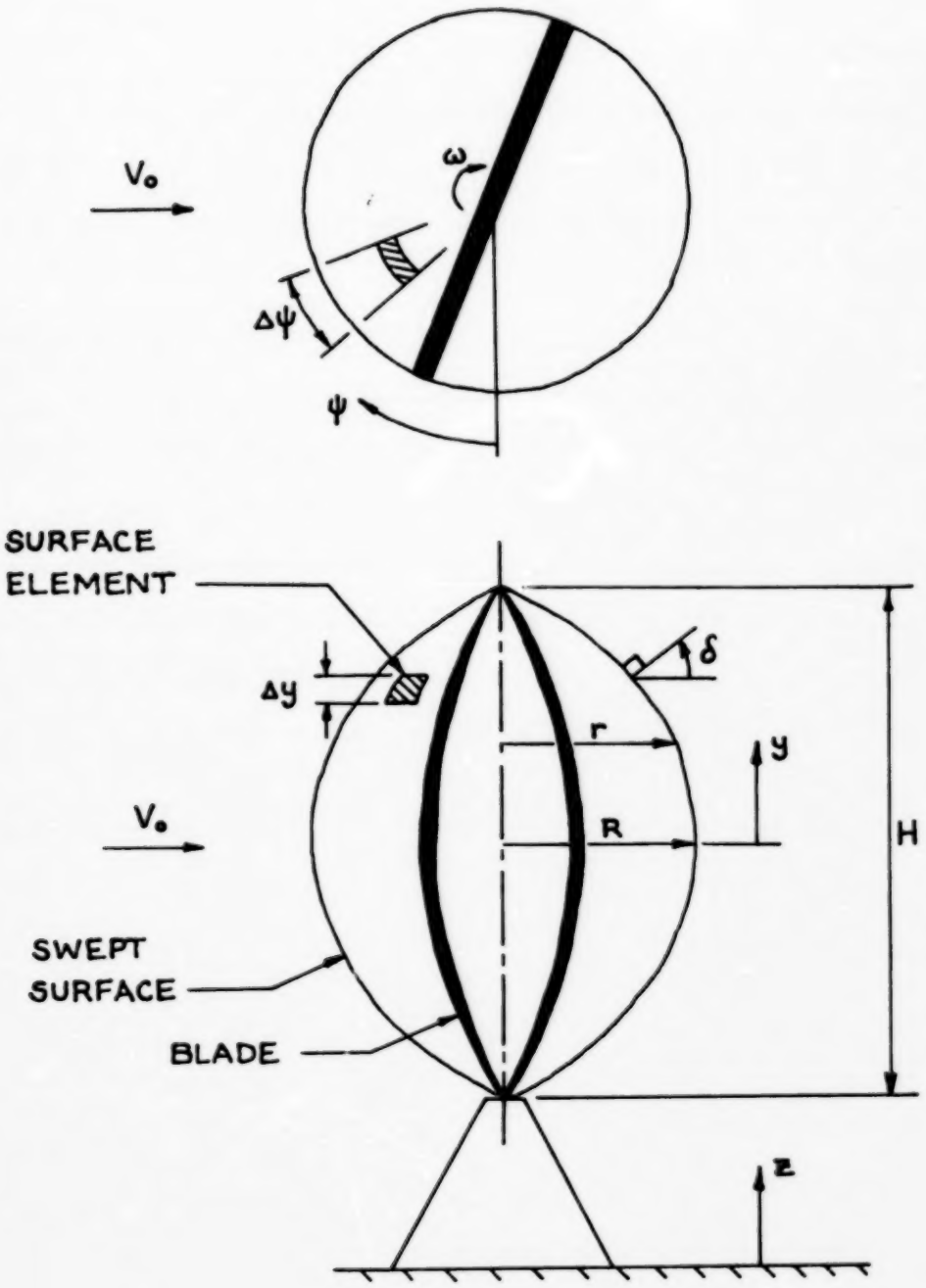


FIG. 1 VAWT AND COORDINATE SYSTEM

at constant RPM in a steady wind condition. The wind may be uniform or it may vary with distance above the ground. Wind profiles may be either power law or logarithmic. In addition, air density and viscosity can be set to different values.

The specification of VAWT geometry can be made in terms of either non-dimensional or dimensional (SI) parameters. The analysis is set up to predict loads and performance of the unit. Performance predictions consist of calculated values for VAWT efficiency, power and torque. As will be described in the following section, these performance data are obtained from an aerodynamic analysis of small blade segments and thus a great deal of detailed information can be made available from the calculations.

3. Theoretical Considerations

The basic aerodynamic theory used in the analysis of the VAWT is the double-multiple streamtube momentum theory developed by Templin (Reference 5). This is an actuator-disk/blade-element type of theory and it is thus reasonably simple and therefore fast, yet it is able to take into account all the main factors affecting VAWT performance. A detailed description of this theory, as used in the present analysis, is given in Reference 1. Incompressible flow is assumed throughout and aerodynamics are assumed to be quasi-steady, except that a crude dynamic stall model is available as an option.

3.1 Coordinate System and Discretization Scheme

The coordinate system is illustrated in figure 1. y and z are vertical coordinates, y being measured from the equatorial plane of the VAWT and z from gound level. The azimuth angle ψ is zero in the radial plane normal to the ambient wind vector on the advancing side of the rotor; ψ is positive in the direction of rotation of the VAWT.

The surface swept by the rotor blades is discretized as follows: it is divided into n_y slices of equal height Δy and

into n_ψ equi-angular segments of angular width $\Delta\psi$. n_y and n_ψ must be even numbers. A typical surface element is shown in figure 1. The equatorial plane ($y = 0$) is a boundary between slices and the $\psi = 0$ plane is a boundary between angular segments.

The flow through the VAWT is considered to be sub-divided into a large number of streamtubes, each of whose cross-sections coincides with a surface element ($r\Delta\psi\Delta y$) at position (ψ,y) on the upstream half of the surface swept by the rotor blades (see figure 2). The streamtube cross-section is also assumed to coincide with the downstream surface element at position ($-\psi$,y).

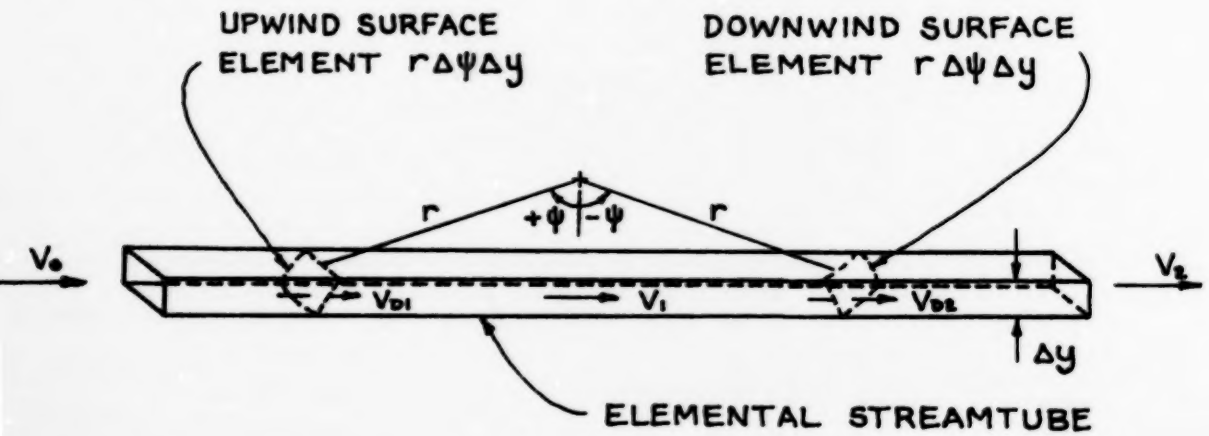


FIG. 2 SKETCH OF ELEMENTAL STREAMTUBE

Although this implies no changes of flow velocity along the streamtube, an assumption which is not strictly correct in the context of the theory, results show that it is quite adequate for an analysis of this level of detail.

3.2 Outline of the Analysis

3.2.1 Double Multiple Streamtube Theory

The double-multiple streamtube theory is an actuator-disk/blade-element theory similar to that which has long been in use for aircraft propellers.

The aerodynamic load on a VAWT blade varies over the blade span and also with the blade's azimuthal position. Consequently, vorticity is shed from the blades. The resulting vortex wake induces a velocity field which influences the aerodynamic forces on the blades. Some theories (e.g. References 6 and 7) for VAWT's attempt a detailed model of the vortex wake in order to determine the velocities seen by a particular element of a VAWT blade. However, such theories are unavoidably complex and require large computing resources. The theory used in the present analysis avoids this complexity by using momentum relations to estimate the velocity induced by the vortex wake at the position

of any particular blade element. This theory represents an improvement over earlier actuator-disk/blade-element theories (e.g. Reference 8) for VAWT's in that it represents the VAWT by two actuator disks, one for the upwind face of the swept surface and the other for the downwind face. Its predictions can thus reflect the differences in flow conditions encountered by blade elements in the upwind and downwind portions of any given streamtube. The 'single' multiple streamtube methods lack this ability.

A typical streamtube is shown in figure 2. The flow in each streamtube is assumed to be completely independent of that in all other streamtubes. The flow in each streamtube is considered to be acted upon by two actuator disks, 'disk 1' being the upstream half of the surface swept by the rotor blades and 'disk 2' being the downstream half of the swept surface. As a result of the forces exerted on the fluid by the actuator disks, its velocity changes along the streamtube. Along any given streamtube, the fluid is assumed to take on five different velocities, as follows (see figure 2):

V_0	ambient wind speed, far upstream of disk 1
V_{D1}	flow speed in the plane of disk 1
V_1	flow speed in the region between the two disks
V_{D2}	flow speed in the plane of disk 2
V_2	flow speed far downstream of disk 2

Equilibrium flow conditions, i.e. no streamwise velocity or pressure gradients, are assumed to prevail at stations 0, 1 and 2 in each streamtube. This implies that the value of velocity V_1 is determined only by effects upstream of station 1 and is not influenced by downstream phenomena such as performance of disk 2. Ambient static pressure is assumed to prevail at stations 0,1 and 2. The flow in the streamtubes is assumed to be steady, in a time-average sense.

By use of Bernoulli's equation it can be shown that

$$V_{D1} = 0.5(V_0 + V_1) \qquad \text{----------} \qquad (3.1)$$

and $$V_{D2} = 0.5(V_1 + V_2) \qquad \text{----------} \qquad (3.2)$$

By applying the momentum equation to a control volume whose sidewalls coincide with the streamtube and which extends from station 0 to station 1 (see figure 2), it can also be shown that

$$\overline{DW}_1 = \rho\, V_{D1}\, (V_0 - V_1) \qquad \text{----------} \qquad (3.3)$$

where $\overline{DW}_1$ is the time-average downwind force per unit streamtube area exerted by the fluid on disk 1. Similarly,

$$\overline{DW}_2 = \rho\, V_{D2}\, (V_1 - V_2) \qquad \text{----------} \qquad (3.4)$$

As Templin (Reference 5) points out, equations (3.1) and (3.2) represent a result of the theory which agrees exactly with a

result of the much more complex vortex field theory of Holme (Reference 6).

The force exerted by the fluid on the actuator disks is, in reality, exerted on the moving blades of the VAWT. Each time a blade passes through a streamtube, the fluid flowing in that streamtube exerts a force pulse on the blade. It is therefore necessary to establish a relation between the time-average force $\overline{DW}$ and the blade forces. Time-averaging can be carried out over a period corresponding to one revolution of the VAWT. Let ΔF_{DW} be the downwind force per unit blade span acting on a blade where it passes through a streamtube. The streamtube cross-section area is given by $r\Delta\psi\Delta y Sin\psi$ (see figure 3) and the span of the blade in the streamtube is $\Delta y/cos\delta$, where δ is defined in figure 1. Each blade spends a period of time $(\Delta\psi/\omega)$ in the upstream part of the streamtube during the period $(2\pi/\omega)$ required for one revolution. Therefore, if there are N blades,

$$\overline{DW}_1 = \frac{N\Delta F_{DW}(\Delta y/\cos\delta)\quad(\Delta\psi/2\pi)}{r\ \Delta\psi\ \Delta y\ \sin\ \psi}$$

$$= \frac{N\Delta F_{DW}}{2\pi r Sin\psi Cos\delta} \qquad \text{----------} \qquad (3.5)$$

Equating this result for $\overline{DW}_1$ with that from equation (3.3) and using the relation $(V_0 - V_1) = 2(V_0 - V_{D1})$, obtainable from equation (3.1), one obtains a quadratic in V_{D1} with the solution

$$V_{D1} = 0.5\left[V_0 + \sqrt{V_0^2 - \frac{N\Delta F_{DW}}{\pi\rho r Sin\psi Cos\delta}}\right] \text{----------} \qquad (3.6)$$

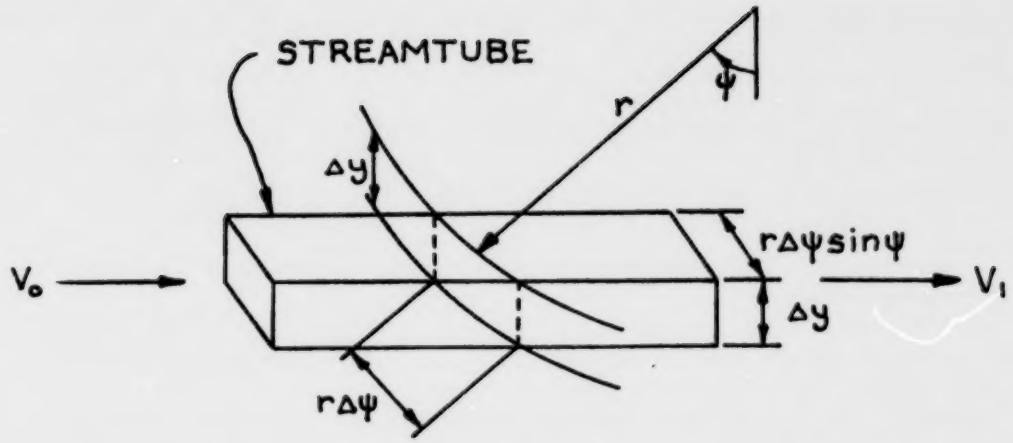


FIG. 3 SKETCH TO ILLUSTRATE CROSS-SECTION AREA OF ELEMENTAL STREAMTUBE

An entirely similar relation can be obtained for the downstream actuator disk; V_1 replaces V_0, V_{D2} replaces V_{D1} and the absolute value of Sin ψ is used.

Equation (3.6) is a key equation and is used in the analysis to solve for V_D. Note that the values of ΔF_{DW} depend somewhat on the values of V_D; an iterative procedure is therefore required for solution of equation (3.6) and determination of the blade forces. It is possible for the term under the square root sign in equation (3.6) to become negative for highly loaded VAWT operating conditions; this would correspond to negative values

of the equilibrium velocity V_1 or V_2 and the assumptions in the theory render it inaccurate even before this breakdown of the equations occurs. The computer program which performs these calculations prints a warning message if this condition is encountered.

The aerodynamic forces acting on the VAWT blades are determined from data for the lift and drag behaviour of the airfoil section used for the blades. These data are available in the form of lift and drag coefficient C_L and C_D *vs* angle of attack for various Reynolds numbers, Re: for example, data for the NACA-0012 airfoil section are shown in figure 4. For the present application the data must cover the angle-of-attack range $-180^o \leq \alpha \leq 180^o$. The calculations have been set up for tabular data; the α and Re intervals between data entries can be arbitrary and linear interpolation on α and Re is used between data entries. Data for any number of airfoil sections can be stored. It should be noted that the drag-coefficient data are presented to the calculation as values of $(C_D - C_{DMIN})$ and the user has the option of specifying a value of C_{DMIN} different from the usual experimental value for the section. C_{DMIN} is the minimum value of the drag coefficient.

The local instantaneous angle of attack α varies with both

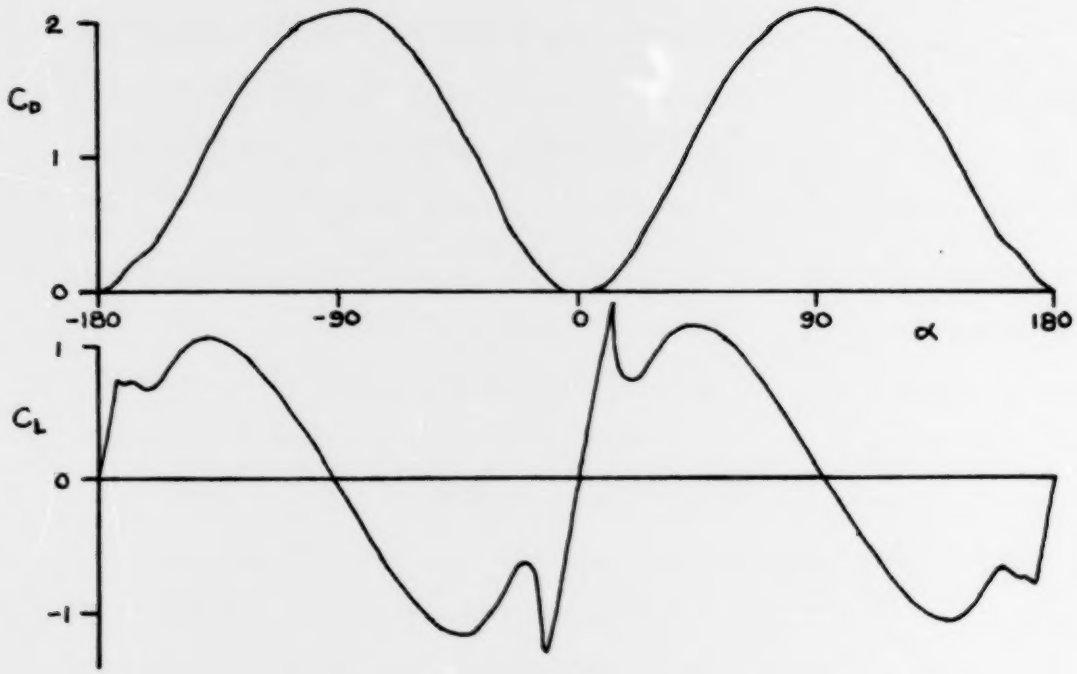
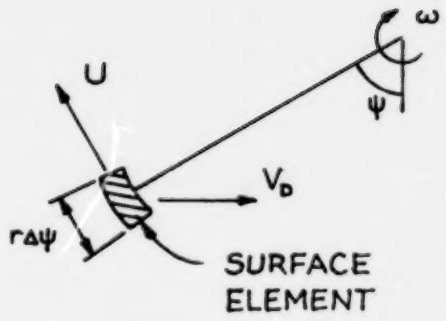


FIG. 4 LIFT AND DRAG CHARACTERISTICS OF NACA 0012 SECTION ($Re = 1.8 \times 10^6$) (from Ref. 11)

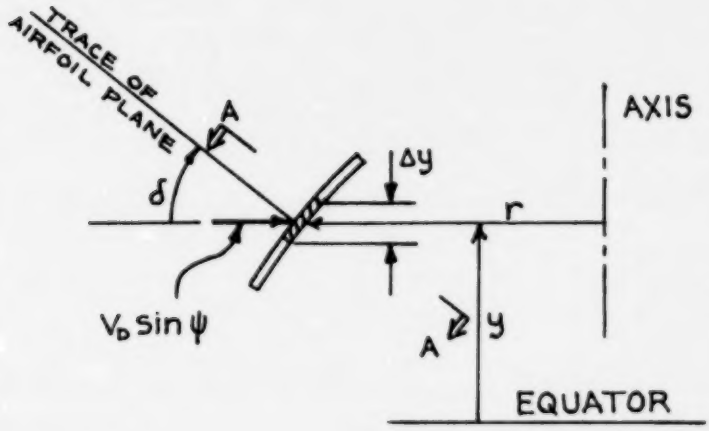
ψ and y on each blade. The local instantaneous values of C_L and C_D are assumed to be the values read from the airfoil data curves or tables for the local instantaneous α value. The only exception to this quasi-steady approach is the optional use of a dynamic stall model when α is near the primary stalling value; this model is outlined in sub-section 3.2.2.

At any position (ψ,y) on the swept surface the 'airfoil plane' is defined as the plane which contains the blade speed vector U and is normal to the swept surface at that point. Velocity components in the airfoil plane are shown in figure 5. Expressions for the angle of attack, α , and the relative velocity, W , can be deduced from the diagrams in figure 5; α is equal to $(\beta + \gamma)$, where γ is the toe-in angle. Knowing α and the section Reynolds number, the lift and drag coefficients, C_L and C_D, can be found from the aerodynamic data. The lift and drag forces can then be resolved to give the coefficients C_T and C_N of the force components tangential and normal to the swept surface. These force components can again be resolved into the downwind and crosswind directions. Knowing the relative velocity, W , the corresponding dimensional force components per unit blade span are easily determined from the force coefficients. The downwind force per unit span, ΔF_{DW}, is then available for use in the iterative solution of equation (3.6). Iteration proceeds until calculated values of V_D have converged.

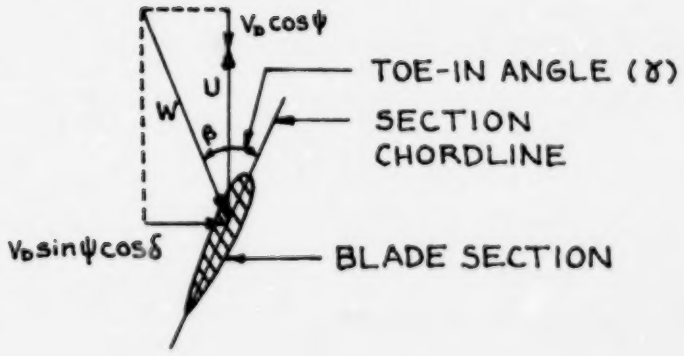
The calculations outlined above are carried out at the upstream and downstream 'disk' in each of the streamtubes established in the discretization scheme outlined in Section 3.1.



a) PLAN VIEW OF VAWT



b) SIDE VIEW ALONG U VECTOR (TANGENT TO AIRFOIL PLANE



c) VELOCITY COMPONENT IN AIRFOIL PLANE (SECTION A-A)

FIG. 5 VELOCITY COMPONENTS IN AIRFOIL PLANE

3.2.2 Dynamic Stall Model

The term 'dynamic stall' refers to the stalling behaviour of an airfoil whose angle of attack, α , is changing with time. If α is increasing rapidly, stall tends to occur at a higher value of α than for static conditions and the reverse is true if α is decreasing rapidly. The observed behaviour of the lift coefficient is sketched in figure 6. In the case of VAWT's, α does vary with time, in some cases sufficiently rapidly that dynamic stall effects are significant. A dynamic stall model is therefore incorporated in the analysis. The calculations are arranged so that the user has the option of by-passing this model.

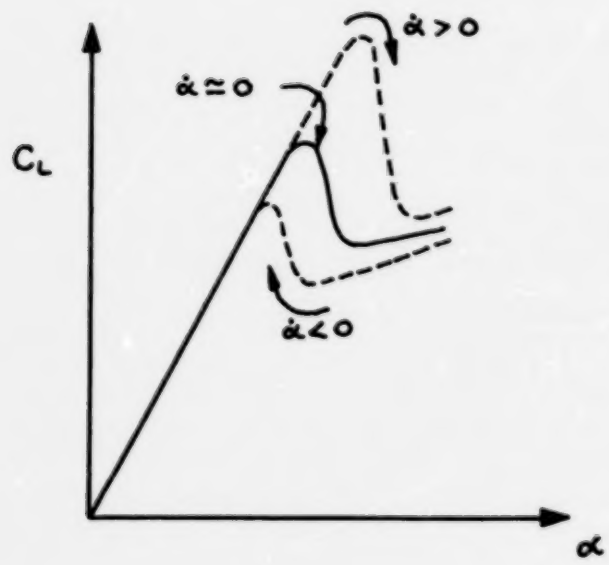


FIG. 6 SKETCH OF DYNAMIC STALL BEHAVIOUR

Dynamic stall is a very complex phenomenon. Although a substantial amount of work has been done in this area, mainly with helicopter applications in mind, only rather crude empirical correlations are currently available for prediction of dynamic stall behaviour (Reference 9). The model of Ericsson and Reding (Reference 9) was developed for the specific case of an airfoil oscillating harmonically in pitch about an axis fairly near the centroid of the section. Unfortunately the formulation is such that when the relations are adapted to suit the VAWT problem, they become physically implausible. It was therefore decided to follow Strickland (Reference 7) in using the Boeing-Vertol model for dynamic stall (Reference 10).

The dynamic stall model assumes behaviour like that sketched in figure 6; that is the lift-curve slope ($\partial C_L/\partial\alpha$) and the zero-lift angle, α_o are assumed to remain unchanged and dynamic effects only modify the angle of attack at which stall occurs. The change in the stalling angle of attack is a function of ($\dot{\alpha}c/W$) and other parameters. In practice, a modified angle of attack, α_m, is calculated and used instead of α to enter the static C_L, C_D vs α data. Reference 1 gives a detailed description of the dynamic stall model.

3.2.3 Loads and Performance

The instantaneous aerodynamic load distribution along a blade at any azimuthal position ψ is given by plots of force component per unit span vs y for that value of ψ. This information is available from the calculations outlined in Section 3.2.1. The corresponding overall instantaneous blade loads are found by numerical integration. The overall time-average torque produced by all blades is obtained by appropriate summation and averaging of the instantaneous blade torque at all ψ values. Power and efficiency are then easily found.

4. The Computer Model

The analysis described in the previous section has been implemented in a computer program and is now available for use. Considerable effort was expended to make the program simple to use and sufficiently flexible that the requirement of most designers can be met in a straightforward manner. The following review of requirements suggests the intention of the program design.

4.1 Model Requirements

The requirements of the wind turbine analysis program were defined at the outset of the project as follows:

1. The language should be FORTRAN IV (1966).
2. It should use the calculation procedure outlined in chapter 3 (double multiple stream tube theory).
3. It must run with both metric and non-dimensional data. If non-dimensional data are specified then only non-dimensional results should be output. Either metric or non-dimensional output are to be provided if dimensional (metric) data are specified.
4. The output should be available at a video terminal, a line printer or a disk file on command.

5. The output should be in three levels:

   Level 1: Overall performance parameters of the wind turbine.

   Level 2: Level 1 plus blade parameters as a function of azimuthal position.

   Level 3: Levels 1 and 2 plus values of various parameters as a function of height for a given azimuth angle (ψ).

6. The program should be able to be used by someone with no knowledge of wind turbine theory and little knowledge of computers.

1.2 General Organization of the Model

The program developed for analysis of the VAWT is very modular. The organization of the primary functions of the calculation are shown in figure 7. As can be seen from the figure, the major modules of the program interact with information which is retained in specific data-bases designated to a particular purpose. The major data blocks shown in figure 7 indicate the type of information that is required by the program and shows where information generated by the program is stored. It should be noted that by carefully structuring these data bases, no information is overwritten or discarded throughout the calculation. This feature of the software design ensures that program output can be changed readily to meet the needs of

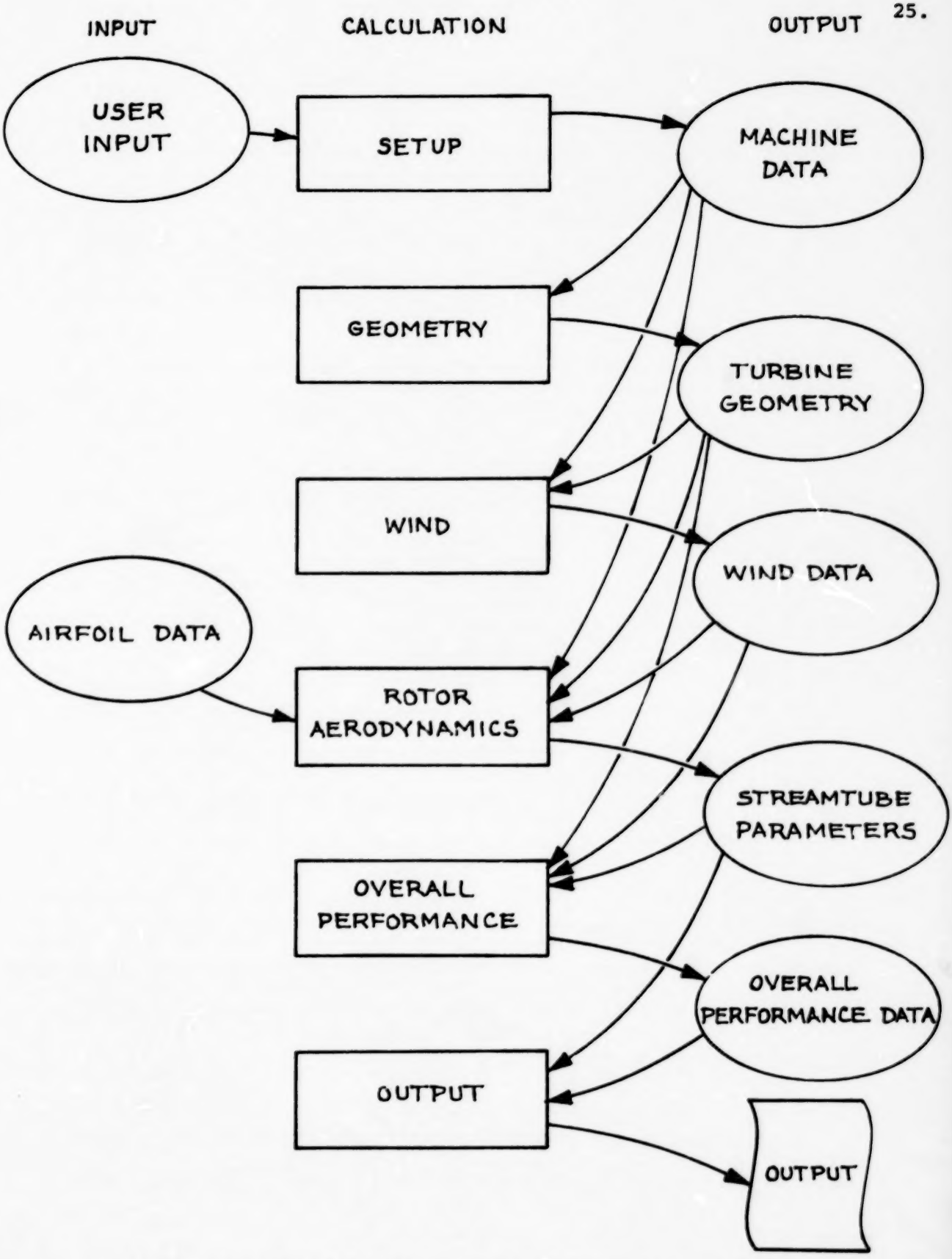


FIG. 7 VAWT ANALYSIS PROGRAM ORGANIZATION

specific designers. Also, new modules can be added by linking directly to the existing data. For example, all of the aerodynamic forces have been retained and inclusion of a stress analysis module would be quite straightforward.

The concept of modularity has been reflected through to overall hierarchy of the program. The primary functions of input, calculation and output have been decomposed into a large number of quite small subroutines. Each subroutine performs a specific function and links only to those data bases required. This highly modular structure has ensured that the program could be easily segmented for implementation on conventional minicomputers. The current configuration consists of two programs, one of which builds a data file from the user input, the other of which computes VAWT performance and outputs these data to the user. The two programs communicate with each other through disk based data files.

The input program is used to create data sets which are stored in user defined disk files. These files are read in by the calculation program, which performs the analysis on the wind turbine defined by that file.

Both programs are controlled in a similar fashion. A main program acts as an executive routine and calls the other

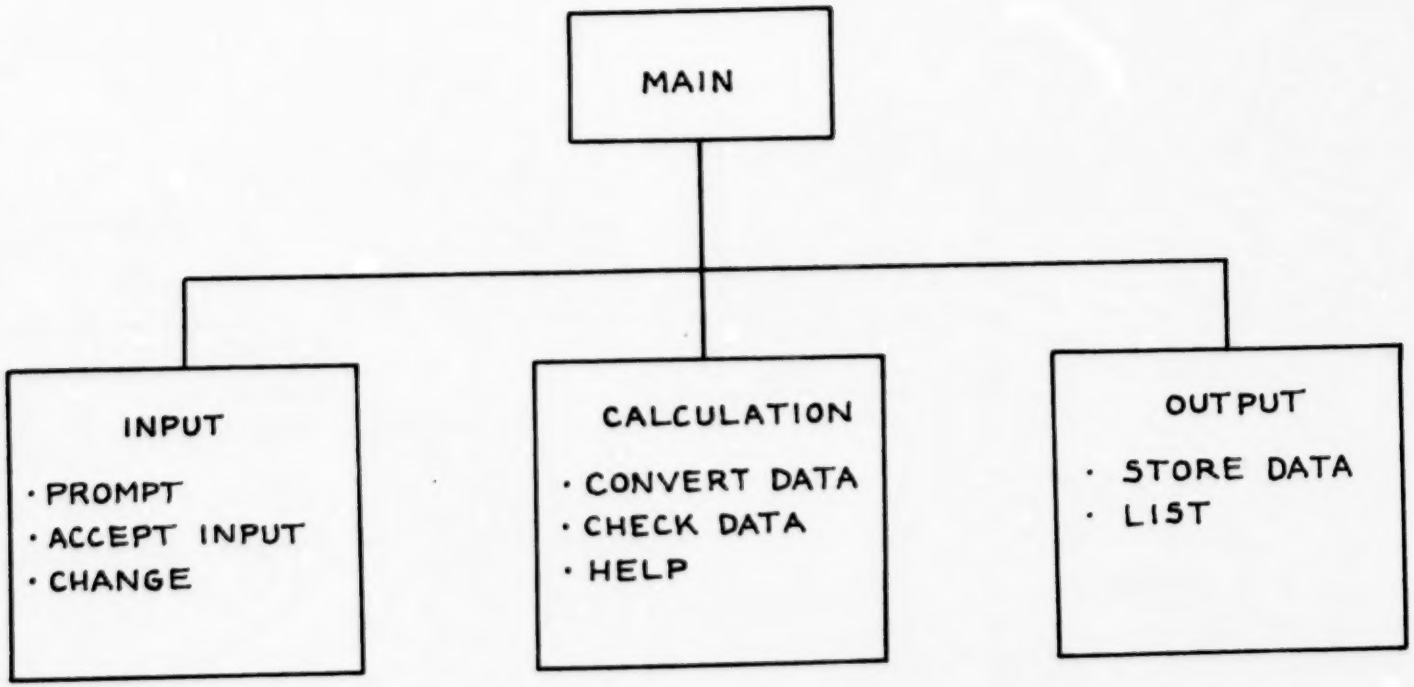


FIG.8 HIERARCHY OF INPUT PROGRAM

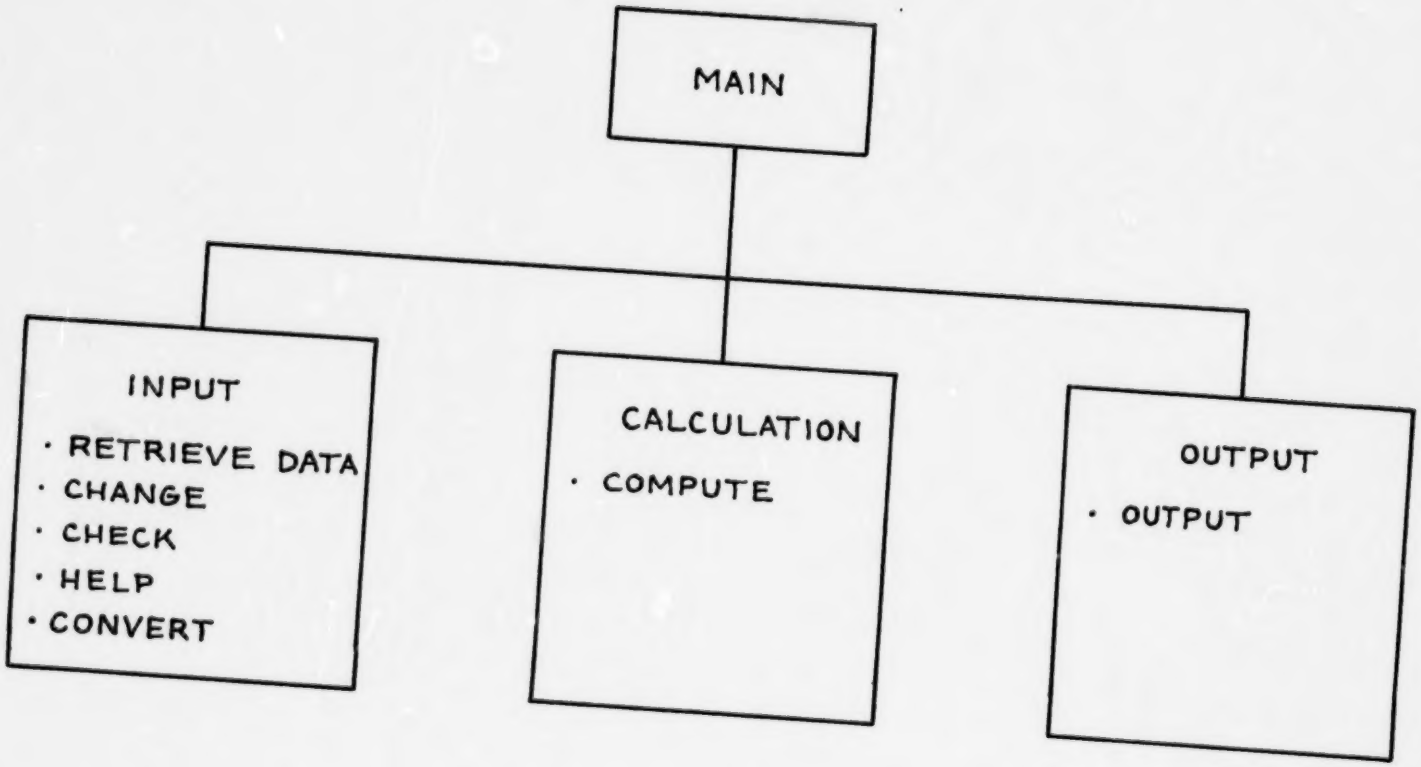


FIG. 9 HIERARCHY OF CALCULATION PROGRAM

subroutines according to user input commands. The structure of the two programs is illustrated in figures 8 and 9.

The use of slices and sectors in the double multiple streamtube method lends itself to the use of two-dimensional arrays for storing the streamtube parameters. However, with twenty different streamtube variables, a large amount of memory space would be required (20 variables x 20 slices x 36 sectors = 14400 variables). To minimize the size of the program, it was set up to calculate the parameters for one slice and store them in a disk file before moving on to the next slice. In this way, the program needs only the capacity to store the streamtube parameters for one slice.

4.3 Data Input

The data that must be provided by the user is that necessary to specify the wind turbine. The form of this information is explained in the following paragraphs.

The following options provide a broad categorization of the complexity with which the wind turbine can be described. In running the program, the user will be asked to select each of these options.

1) Dimensional or Non-dimensional data

2) Uniform or Non-uniform wind velocity profile

3) Log law or Power law wind velocity profile

4) Parabolic or Non-parabolic turbine radius.

Once the major options have been selected, the following input data is required by the program. Either dimensional or non-dimensional data may be entered, but not both.

These inputs are output as a record for the user the first time output is requested with that data set.

Non-Dimensional Input Data

Height to diameter ratio (H/2R)

Solidity (NC_o/R)

Equatorial elevation (Z_E/R) (for non-uniform wind)

Toe-in angle at equator (degrees)

Reynolds number ($\omega RC_o/\nu$)

Minimum drag coefficient

Table of chord (C/C_o) and toe-in (γ/γ_o)
vs. height (y/(H/2))(if variable)

Table of radius (r/R) vs. height (y/(H/2))
(if not parabolic)

Reference Wind Velocity ($V_{oref}/\omega R$)

Reference Elevation (Z_{ref}/R) (for non-uniform wind)

Exponent (for power law)

Roughness parameter (Z_o/R) (for log law)

No. of Slices

No. of Sectors

Dimensional Input Data

Airfoil Section I.D.

Height (m)

Radius at Equator (m)

No. of Blades

Rotational Speed (rpm)

Minimum drag coefficient

Elevation at Equator (m) (for non-uniform wind)

Chord (m) (if constant)

Toe-in angle (degrees) (if constant)

Table of chord and toe-in vs. height (if variable)

Reference Wind Velocity (m/s)

Reference Elevation (m) (for non-uniform wind)

Exponent (for power law)

Roughness Parameter (m) (for log law)

Density (kg/m^3)

Viscosity (m^2/s)

Table of radius vs. height (if not parabolic)

No. of Slices

No. of Sectors

4.4 Data Output

The output available in this program is divided into three levels of detail and is available in either dimensional (SI) or non-dimensional form.

The first level includes the overall performance parameters for the turbine. An example of level 1 output is shown below.

```
*** OVERALL PERFORMANCE ***

Output power:                  43.154 kW
Efficiency:                     7.79 %
Total torque:                  10.30 kN.m
Total downwind force:           4.21 kN
Total crosswind force:          0.04 kN
Swept area:                   266.66 sq.m
  CQ=   0.0280      CP=   0.0783
  KQ=  0.00359      KP=  0.00359
```

The second level of output consists of a table of turbine blade forces as a function of azimuthal position. With non-dimensional output, the user is given the choice of obtaining the results in the form of dimensionless coefficients referenced to the wind speed (C) or referenced to the blade speed (K). An example of level 2 output is shown below.

*** BLADE FORCES (NEWTONS) ***

PSI	TANGENTIAL	NORMAL	DOWNWIND	CROSSWIND	TORQUE(N.m)
10.0	81.5	1947.3	180.5	1493.0	603.0
30.0	668.9	5332.3	1481.4	3903.7	4936.9
50.0	1401.8	7292.3	3486.9	4755.8	10908.4
70.0	1361.3	6602.9	4486.4	3081.6	11153.3
90.0	790.9	4494.4	3623.2	790.9	6757.6
110.0	529.3	3181.0	2623.0	-391.4	4580.1
130.0	392.9	2301.7	1717.1	-927.9	3472.1
150.0	404.3	1972.1	1186.7	-1246.8	3591.2
170.0	69.0	720.5	170.3	-568.7	574.0
190.0	67.9	-718.1	168.9	566.8	563.9
210.0	401.1	-1981.6	1186.9	1253.5	3552.5
230.0	409.7	-2355.0	1764.1	945.5	3621.4
250.0	550.0	-3219.1	2662.0	383.6	4759.9
270.0	818.5	-4549.2	3672.1	-818.5	6999.7
290.0	1381.2	-6633.9	4507.4	-3110.4	11315.3
310.0	1303.3	-6942.7	3329.8	-4495.3	10073.7
330.0	634.8	-5155.9	1440.4	-3764.3	4665.1
350.0	80.1	-1924.8	178.7	-1475.0	592.3

The third level of output allows the user to examine the streamtube parameters along a blade at a specified azimuthal position. Output includes blade forces and angle of attack and can be obtained for any number of azimuth angles. Again the user is given the option of obtaining K's or C's. An example of level 3 output is shown below.

*** STREAMTUBE PARAMETERS ***

Azimuth angle = 90.0 degrees

Slice	alpha	Fdw(N/m)	Fcw(N/m)	Ft(N/m)	Fn(N/m)	Q(N.m/m)
10	42.26	11.05	-1.41	-1.41	22.76	-2.67
9	22.00	49.84	14.31	14.31	85.75	72.97
8	18.40	134.56	36.27	36.27	190.30	272.05
7	18.34	240.52	53.53	53.53	280.49	487.15
6	19.18	320.17	61.06	61.06	326.51	604.54
5	19.18	320.17	61.06	61.06	326.51	604.54
4	18.34	240.52	53.53	53.53	280.49	487.15
3	18.40	134.56	36.27	36.27	190.30	272.05
2	22.00	49.84	14.31	14.31	85.75	72.97
1	42.26	11.05	-1.41	-1.41	22.76	-2.67

The output is arranged so that requesting a certain level results in all lower levels of output being displayed as well (eg. requesting level 3 will result in levels 1, 2 and 3 being output).

In the case where the user has chosen to work with dimensional (SI) data, he will be given the option of obtaining the non-dimensional results. If non-dimensional data is chosen, only non-dimensional results can be output.

Model Usage

The use of this computer model was intended to be quite simple. The programs are set up so that the user interacts with the programs through a menu of commands and gives the instructions rather than answering questions asked by the computer. This interactive arrangement makes the user constantly in control and aware of what the program is doing. The commands available in each program are listed below.

Menu for Input Program

Build data set

Edit data set

List data on terminal

List data on line printer

Save data on disk file

Terminate

Menu for Calculation & Output Program

Read data from disk file

Edit data set

Output level 1 results

Output level 1 and 2 results

Output level 1, 2 and 3 results

Select dynamic stall option

Bypass dynamic stall option

List data set

Direct output to terminal

Direct output to line printer

Terminate

A detailed user's manual (Reference 4) is available.

5.1 Data Preparation and Input

The procedure for inputting the wind turbine data is quite simple. Once the user decides to build a data set, the program will prompt him for all the necessary information (see section 4.3). The user simply answers a few questions and then fills in the required data following the prompts. He must input the data entirely in dimensional or non-dimensional form; not a combination of the two.

In the input program any number of data sets can be created and stored during a run.

A common problem with FORTRAN is the need for the user to be aware of the format of the numbers he is entering. In this program, this problem is avoided by reading all the input data in the form of alpha-numeric characters. These characters are then converted to the appropriate number by a decoding routine.

The airfoil data is prepared in a separate disk file. The set of data chosen by the user in the input routine is read from this disk file by the calculation routine. The data file can be added to or modified at any time, if new airfoil data becomes available.

5.2 Running and Obtaining Results

In order to obtain results, the user simply requests the desired level of output. He does not have to instruct the program to perform the calculations. The program contains a flag which indicates whether the calculations have been performed for the current set of data. If they haven't, the program does the calculations and displays the output. If results are requested and the data has not been modified since the calculations were last done, the program displays the results which

remain in its memory or in the disk file used to store the streamtube parameters.

Before requesting output the user can direct the output to the terminal or a line printer by typing a command from the menu. He can also select to use or bypass the dynamic stall option.

5.3 Parameter Change and Re-runs

To increase the convenience of the program, a feature was included which allows the user to edit his data set and change the value of any or all of the input parameters during a given session.

The user simply enters an edit mode and makes all the modifications he wishes. After exiting the edit mode he can request a certain level of output upon which the program will re-do the analysis and output the results.

This feature is provided for the situation where many runs are to be performed on a specific wind turbine with systematic changes to one or more design parameters. A single data file saves the data for the basic machine and variations on these

data are made during program running.

.4 Other Features

To further simplify the use of these programs several other features have been included.

At any time during the running of either program the user can request a list of the data set. This list can be printed or displayed on the terminal.

Also included in this program is a data checking function. After data are input or modified, the data set is checked to see that the values define physically reasonable situations. Any errors found cause a message to be displayed on the screen. The user can then use the edit feature to fix the appropriate values.

Help messages are provided throughout the program to assist the user in correcting any errors he might have made.

6. Conclusions

A computer program has been written to perform aerodynamic analysis of vertical axis wind turbines. It uses the double multiple streamtube method developed by Templin (Reference 5).

The program was written to be highly interactive. It allows the use of either dimensional or non-dimensional parameters and offers output in three levels of detail.

The program was implemented in FORTRAN IV (1966) on a DEC PDP-11 mini-computer (nominal memory size = 64K). The division of the program into two modules allowed this to be accomplished without the use of overlays.

The structure of the program was made very modular. The use of many subroutines makes future modifications to the program quite simple. Modules can be removed or added with a minimum of change required to the rest of the code.

The program results were compared with the results from other theories as well as available test data and the agreement was found to be good in both cases.

The program has been used by several engineers and its

interactive features were judged to be satisfactory for casual users.

The program is fully documented and reports are available discussing the analysis (Reference 1), the program design (Reference 2), the program testing (Reference 3) and program usage (Reference 4).

The program source code is available through the National Research Council of Canada (NRC) along with any or all of the above documents.

REFERENCES

1) R.J. Kind,

"Analysis Report: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", GasTOPS Limited report GTL-TR-19-10.1, prepared for NRC under Contract No. 13SR.31155-2-4601, June 1982.

2) K.N. Goddard,

"Program Document: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", GasTOPS Limited report number GTL-TR-19-10.2, prepared for NRC under Contract No. 13SR.31155-2-4601, October 1982.

3) "Test Report: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", GasTOPS Limited report number GTL-TR-19-10.3, prepared for NRC under Contract No. 13SR.31155-2-4601, November 1982.

4) "User's Manual: Computer Program for Aerodynamic Analysis of Vertical Axis Wind Turbine", GasTOPS Limited report number GTL-TR-19-10.4, prepared for NRC under Contract No. 13SR.31155-2-4601, November 1982.

5) Templin, R.J.

"New Momentum Theory (Double Multiple Streamtube) for Computation of Curved-Blade Vertical Axis Wind Turbine Performance and Loading",
unpublished manuscript, September 1979.

6) Holme, O.

"A Contribution to the Aerodynamic Theory of the Vertical-Axis Wind Turbine",
proc. Int. Symp. on Wind Energy Systems, BHRA, Cambridge, England, Paper C4, 1976.

7) Strickland, J.H., Smith T. and Sun, K.,

"A Vortex Model of the Darrieus Turbine: and Analytical and Experimental Study",
final report re: Sandia Contract No. 13-5602, Texas Tech University, Lubbock, Texas 1981.

8) Templin, R.J.

"Aerodynamic Performance Theory for the NRC Vertical-Axis Wind Turbine",
NRC, LTR-LA-160, June 1974.

9) Ericsson, L.E. and Reding, J.P.

"Engineering Analysis of Dynamic Stall",
proc. ASME Winter Annual Meeting, San Francisco, Dec. 1978.
No. H00118, pp. 117-123.

10) Gormont, R.E.

"A Mathematical Model of Unsteady Aerodynamic and Radial Flow for Application to Helicopter Rotors",
U.S. Army Air Mobility R&D Lab. Report on Boeing-Vertol Contract DAAJ02-71-C-0045 May (1973) (as cited in Reference 7).

11) Riegels, F.W.

"Aerofoil Sections",
Butterworths, London, 1961.

Appendix 1

The VAWT analysis program was implemented on a Digital PDP-11 running under the RT-11 operating system. The program's specifications, as it exists on that machine, and typical hardware requirements are listed below.

Program Specifications

Language:	FORTRAN IV	
Program size:	22000 words	(input)
	19000 words	(calculation)
No. of lines:	1500	(input)
	2000	(calculation)
No. of executable lines:	1000	(input)
	1250	(calculation)

Typical Hardware Requirements

CPU:	16 bit microprocessor	
Memory capacity:	64 kilobytes	
Devices:	video terminal	
	hard copy printer	(optional)
	disk drive	
Disk capacity:	≈ 1500 blocks	
	≈ 800 kilobytes	